

# Overview of Variable-Speed Power-Turbine Research

The vertical take-off and landing (VTOL) and high-speed cruise capability of the NASA Large Civil Tilt-Rotor (LCTR) notional vehicle is envisaged to enable increased throughput in the national airspace. A key challenge of the LCTR is the requirement to vary the main rotor speeds from 100% at take-off to near 50% at cruise as required to minimize mission fuel burn. The variable-speed power-turbine (VSPT), driving a fixed gear-ratio transmission, provides one approach for effecting this wide speed variation. The key aerodynamic and rotordynamic challenges of the VSPT were described in the FAP Conference presentation. The challenges include maintaining high turbine efficiency at high work factor, wide (60 deg.) of incidence variation in all blade rows due to the speed variation, and operation at low Reynolds numbers (with transitional flow). The PT-shaft of the VSPT must be designed for safe operation in the wide speed range required, and therefore poses challenges associated with rotordynamics. The technical challenges drive research activities underway at NASA. An overview of the NASA SRW VSPT research activities was provided. These activities included conceptual and preliminary aero and mechanical (rotordynamics) design of the VSPT for the LCTR application, experimental and computational research supporting the development of incidence tolerant blading, and steps toward component-level testing of a variable-speed power-turbine of relevance to the LCTR application.



# Fundamental Aeronautics Program

## *Subsonic Rotary Wing Project*

Overview of variable-speed power-turbine research

Dr. Gerard E. Welch  
Technical Lead, Propulsion/Engines

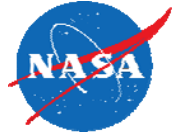


2011 Technical Conference  
March 15-17, 2011  
Cleveland, OH

[www.nasa.gov](http://www.nasa.gov)

# VSPT research team

---



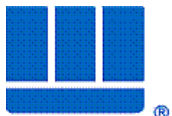
## NASA in-house

- ARL-VTD / G. Skoch, D. Thurman
- NASA RTT / A. McVetta, S. Chen, Dr. G. Welch
- NASA RTM / C. Snyder
- NASA RXN / Dr. S. Howard
- NASA DER / M. Stevens
- ASRC / Dr. P. Giel
- U. Toledo / Dr. W. To
- Ohio State U. / Dr. A. Ameri

## RTAPS contracts on VSPT



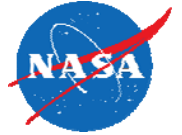
**Rolls-Royce**



**Williams International**

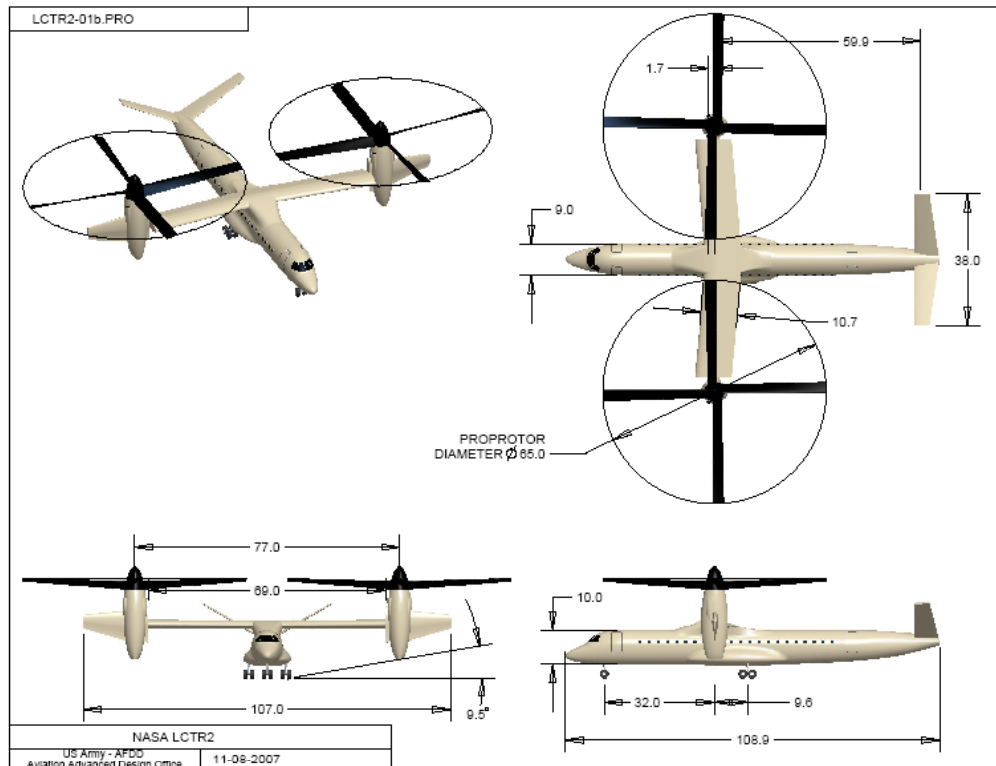
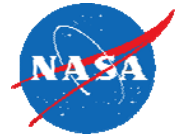
# Overview of VSPT research

---



- Introduction
  - Need for variable-speed tilt-rotor
  - Solution approach using variable-speed power turbine (VSPT)
- Key technical challenges / research needs
- Research activities
- Summary

# Alleviate airport congestion utilizing LCTR



Acree, C. W., Hyeonsoo, Y., and Sinsay, J. D.,  
“Performance Optimization of the NASA Large  
Civil Tiltrotor,” *Proc. International Powered Lift  
Conference*, London, UK, July 22-24, 2008.

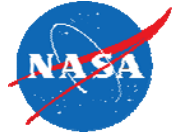
## Large Civil Tilt-Rotor

TOGW	108k lb <sub>f</sub>
Payload	90 PAX
Engines	4 x 7500 SHP
Range	> 1,000 nm
Cruise speed	> 300 kn
Cruise altitude	28 – 30 kft

**Principal challenge** for  
LCTR is required variability  
in main-rotor speed:

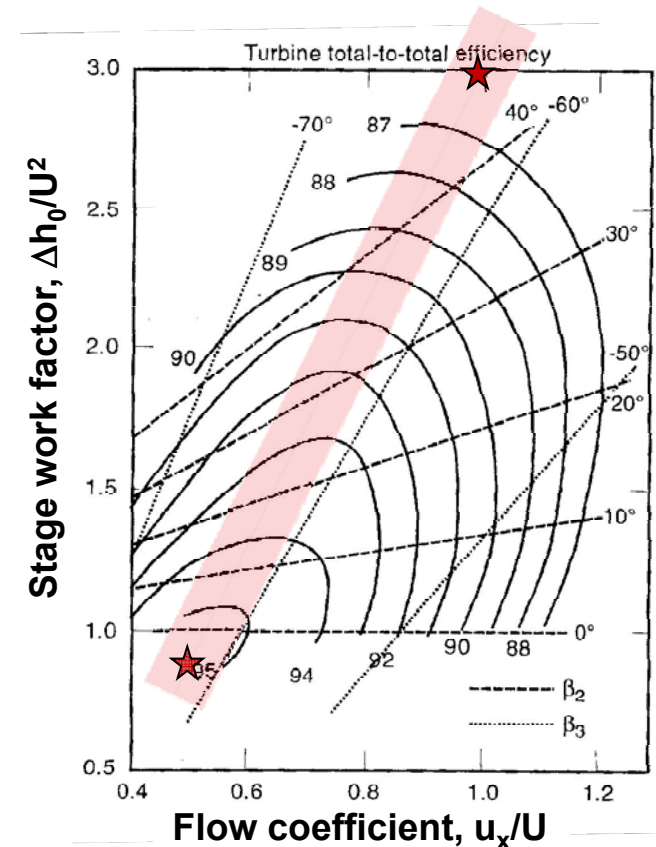
- 650 ft/s VTOL
- 350 ft/s at Mn 0.5 cruise

# Approach to vary main-rotor speed

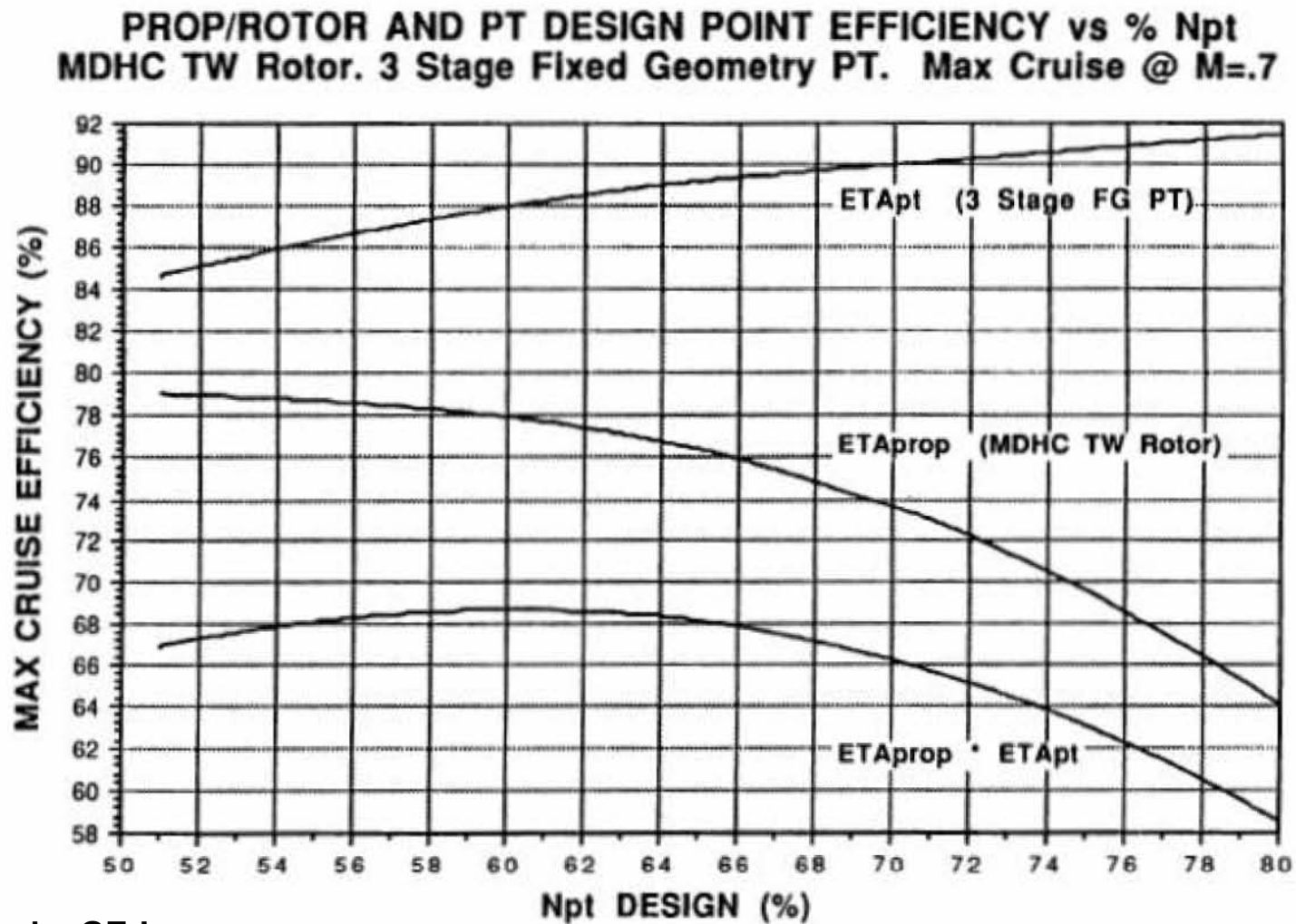


- Fixed-speed PT w/ multi-gear-ratio transmission
  - High efficiency design-point operation from take-off to cruise
  - Complexity and weight of variable transmission
  - Need to shift gears
- Variable-speed PT w/ fixed gear-ratio transmission
  - Wide PT speed range,  
 $54\% < N_{PT} < 100\%$
  - Lower efficiency potential
  - Added weight to turbine/shafting

**Avoid complexity and weight of variable transmission & the need to shift gears**



# Impact of variable-speed power turbine on cruise efficiency



Martin D'Angelo, GE-Lynn  
NASA CR/1995-198380

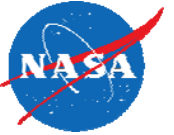
# Key technical challenges for VSPT

---



- Aerodynamics
  - Efficiency at high work factor
  - Incidence variation required by speed change
  - Operation at low Reynolds number
- Rotordynamics
  - Avoidance / management of shaft modes through speed range

# Aerodynamics – efficiency at high work factor



- Specific power is approximately 200 SHP/(lb<sub>m</sub>/s) at 2 kft take-off and 28 kft cruise

$$\dot{W} / \dot{m} = \Delta h_0 = \Delta(u_\theta r \Omega) \approx \text{Const}$$

- If 50% speed reduction

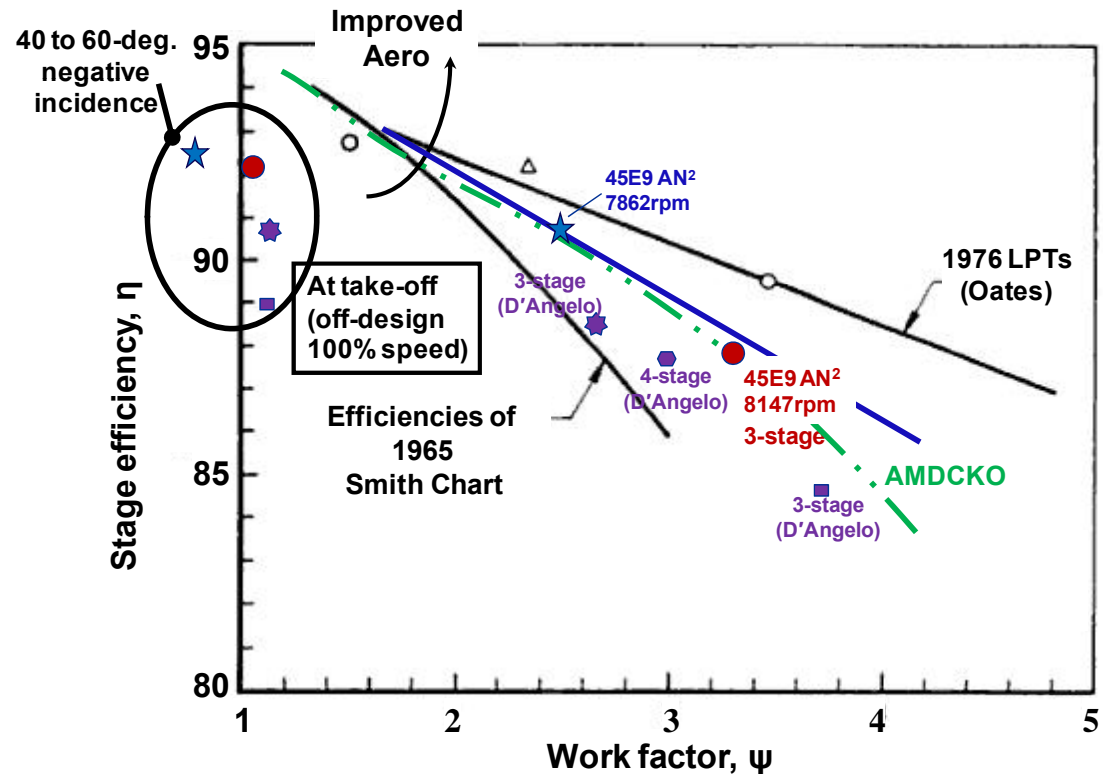
$$r\Omega \downarrow 2$$

then

$$\Delta u_\theta \uparrow 2$$

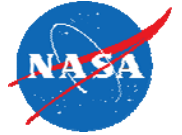
and

$$\psi = \frac{\Delta h_0}{U^2} \uparrow 4$$

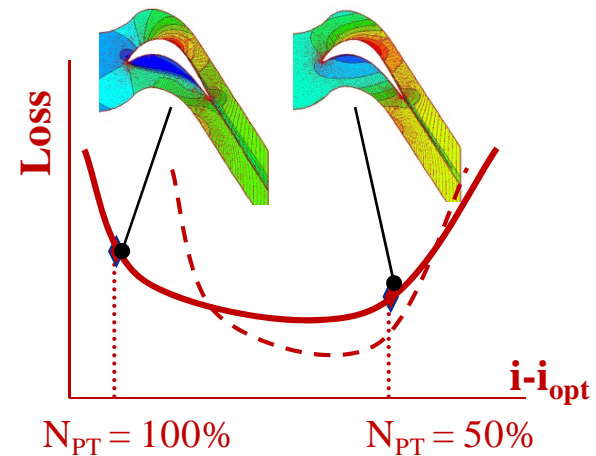


Design-point efficiency vs. work factor

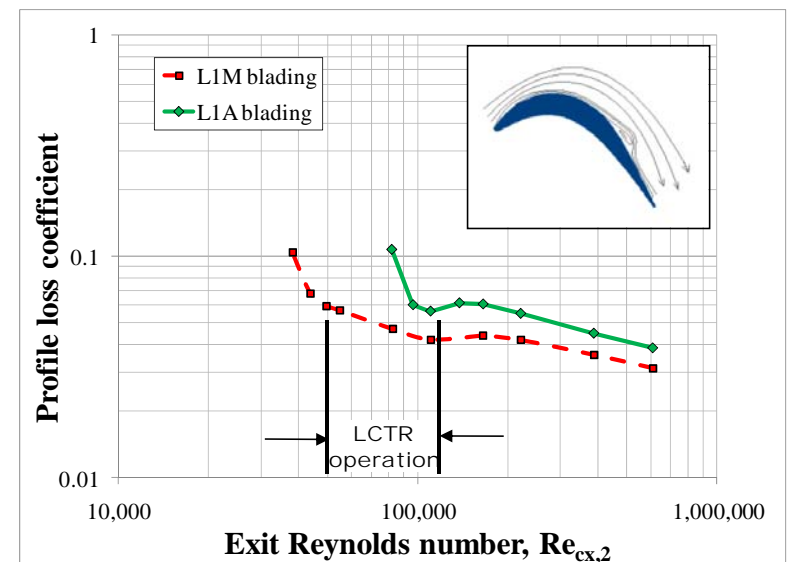
# Incidence variation & low Reynolds number



- Required incidence variation with speed
  - Impact of aerodynamic loading level (Zweifel)
  - Impact of loading schedule
  - Use of variable stators/EGVs
- Low Reynolds number at take-off and cruise (30 to 50k/in.)
  - Impact on design-point loss (efficiency lapse)
  - Impact on incidence-range at acceptable loss levels
  - Influence of unsteadiness

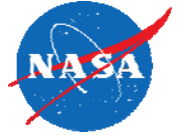


Blade row loss vs. incidence

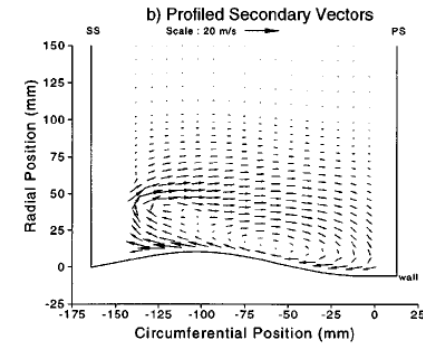


High-load LPT blade at low-Re

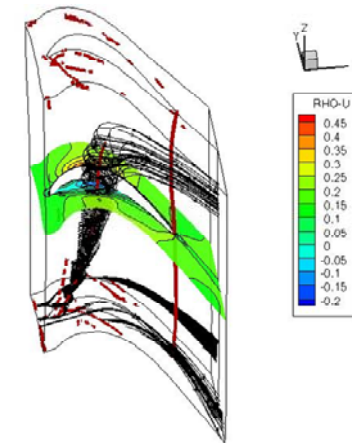
# VSPT aero research and technology development needs



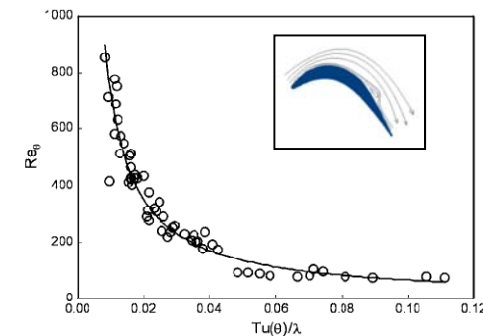
- MDO of variable-speed PT at component and engine level
- Efficient high-load, high-turn aerodynamics
  - Secondary flow management using 3-D blading (lean and bow) and endwall contouring
- Aerodynamics of high negative incidence
  - Characterize 2-D and 3-D loss mechanisms at high (40 to 60 deg.) negative incidence
- Aerodynamics of low-Re number flows
  - Turbulence sub-models for transitional flow into RANS/URANS solvers
  - Multistage experiments and 3-D URANS simulation capability – unsteadiness



Harvey *et al.*, 2000



Rotor 1 at take-off



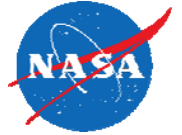
Praisner and Clark, 2007



# RESEARCH ACTIVITIES

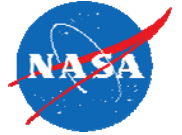
# Research activities

---



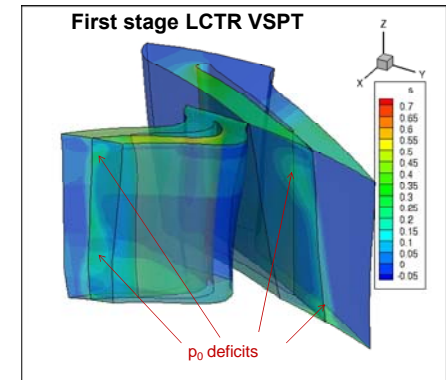
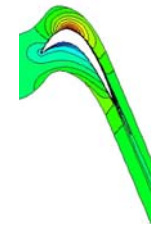
- Conceptual aero-design, optimization, and analysis
- Cascade testing of incidence-tolerant blading
- Computational methods for LPT/PT
- Rotordynamics of LCTR PT rotor
- VSPT component / engine testing

# Conceptual aero-design of VSPT for LCTR

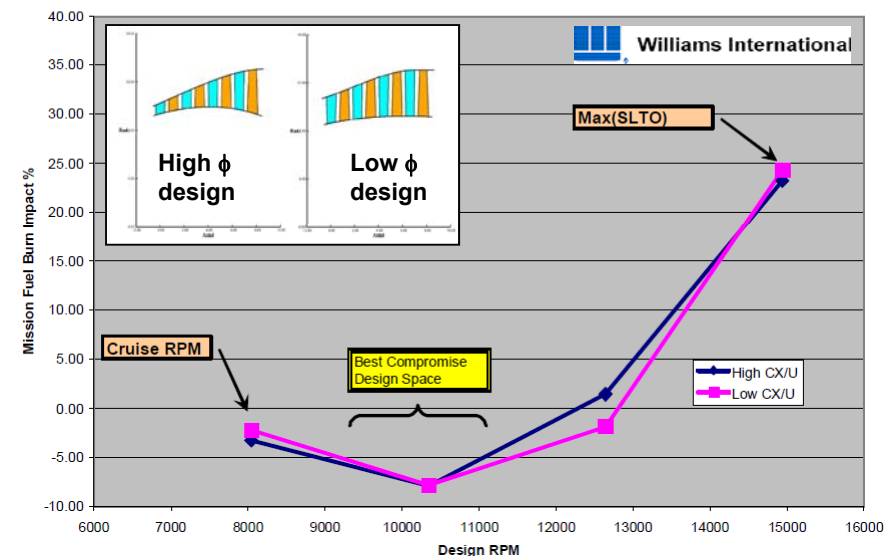


- In-house effort (AFRL TDAAS system)
  - Meanline analysis using F. Huber's meanline tools
  - Design at cruise with  $AN^2$  limit at take-off: 4-stage
  - 2-D blade profiles set in AFRL TDAAS
  - 3-D analysis using SWIFT RANS mixing-plane code

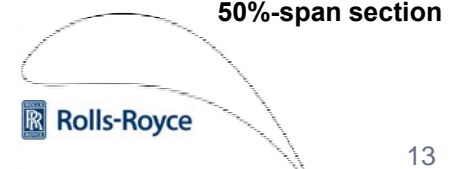
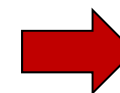
$Z = 1.1$ , 120-deg. turning



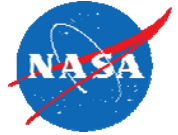
- Williams International study contract
  - Mission fuel burn sets design speed
  - Evaluated work and flow coefficients and blade thickness (nominal & thin): 4-stage
  - FOILGEN (blades) & VORTEX (analysis)



- Rolls-Royce (RRC / RR-NAT) study contract
  - Tailored to high flow coefficient
  - Technology curves: 4-stages
  - Loss buckets biased to +5-deg. incidence at cruise
  - Optimized blade shapes using AIRFOILOPT



# 3-D computational analysis of embedded stage with speed variation

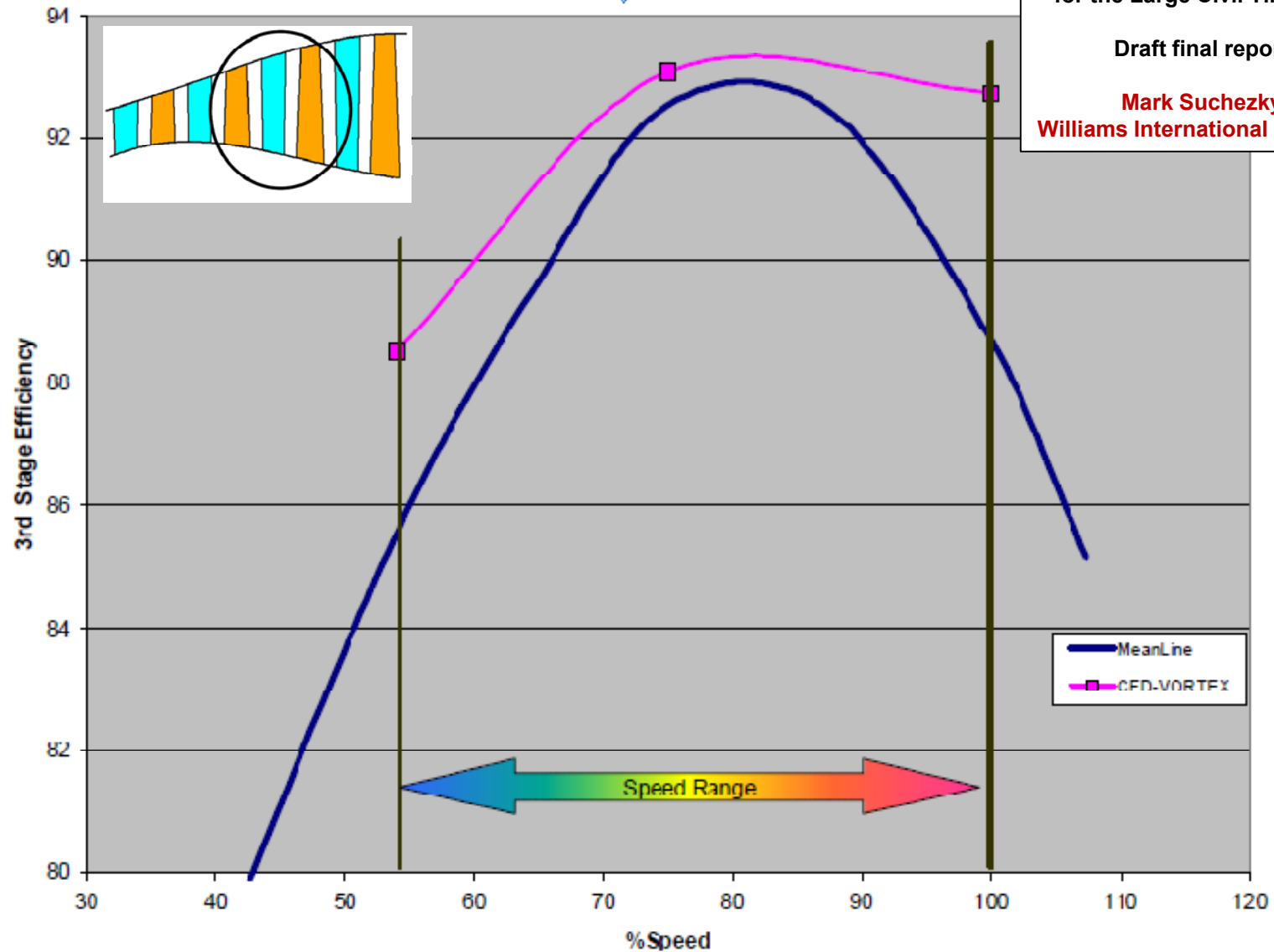


Williams International

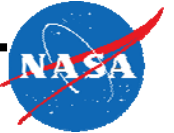
Variable-speed power turbine  
for the Large Civil Tilt Rotor

Draft final report

Mark Suchezky  
Williams International Co., LLC



# 3-D computational analysis of rotor of 4-stage VSPT

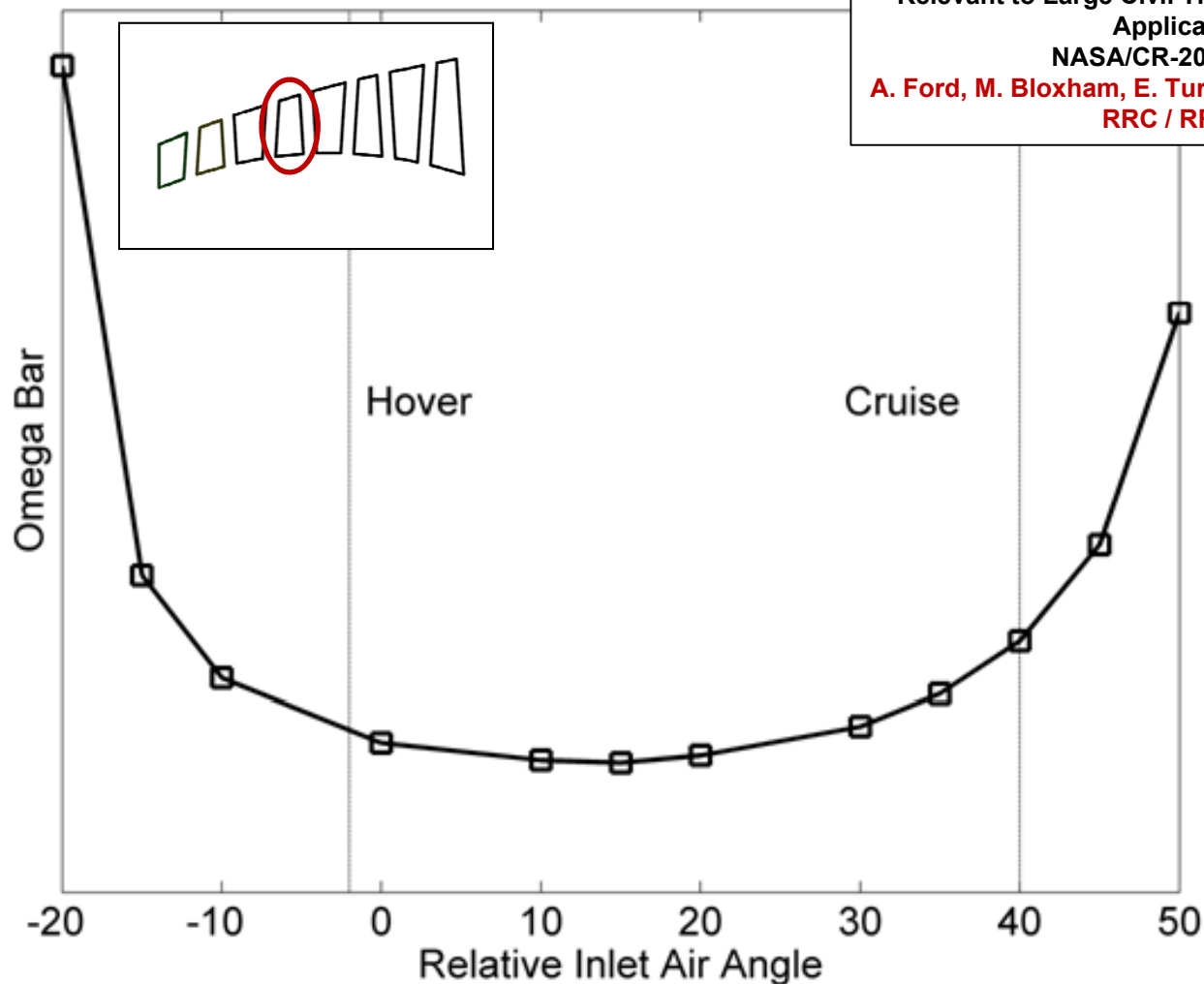


Rolls-Royce

RTAPS VSPT Contract NNC10BA14B  
Design Optimization of Incidence-Tolerant Blading  
Relevant to Large Civil Tilt-Rotor Power Turbine  
Applications

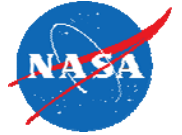
NASA/CR-2011-217016

A. Ford, M. Bloxham, E. Turner, E. Clemens, S. Gegg  
RRC / RR-NAT

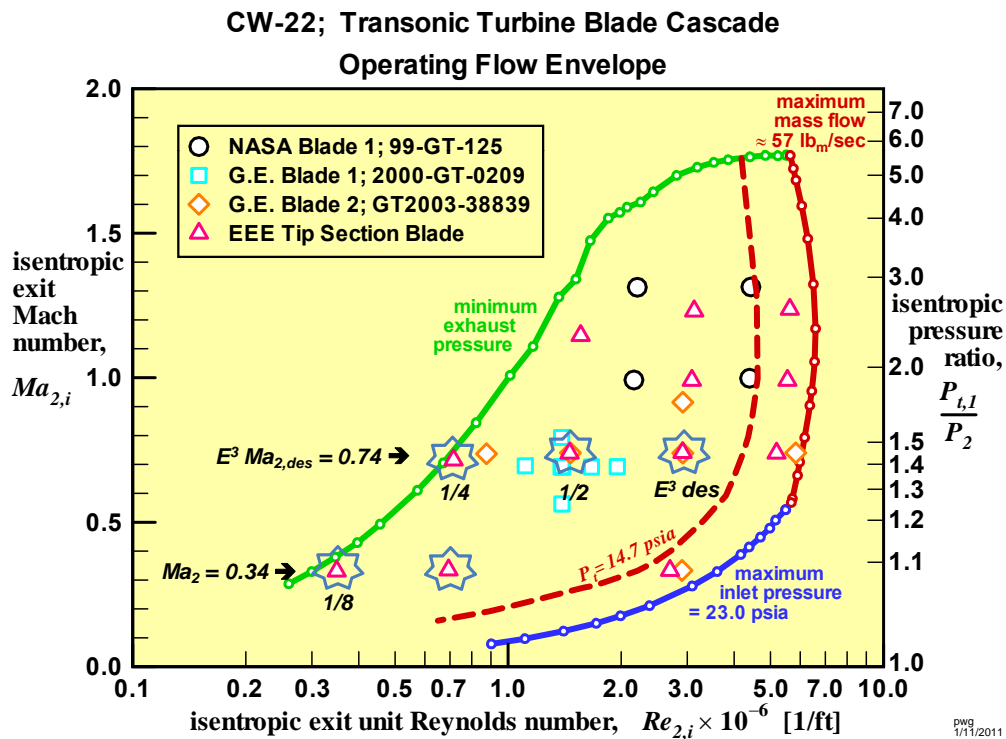


Loss bucket of embedded rotor 2 of 4-stage VSPT

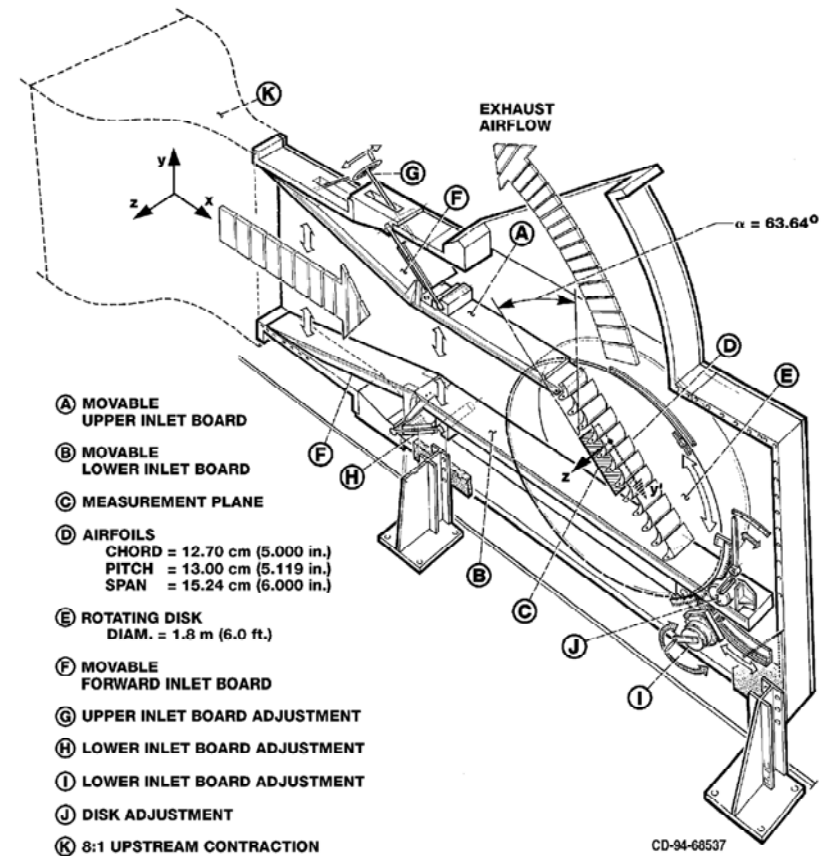
# NASA GRC transonic linear cascade



- Aero and heat transfer testing at wide range of  $M$ ,  $Re$ ,  $Tu$ , and flow incidence.



**Tunnel test conditions**

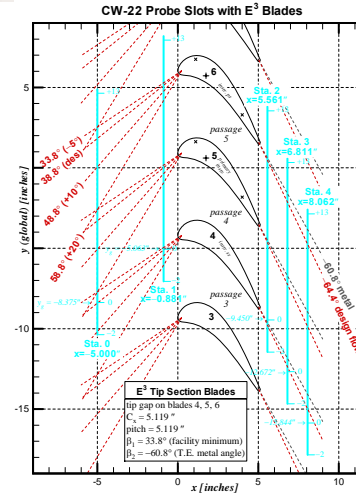


**Schematic diagram of NASA  
transonic linear cascade**

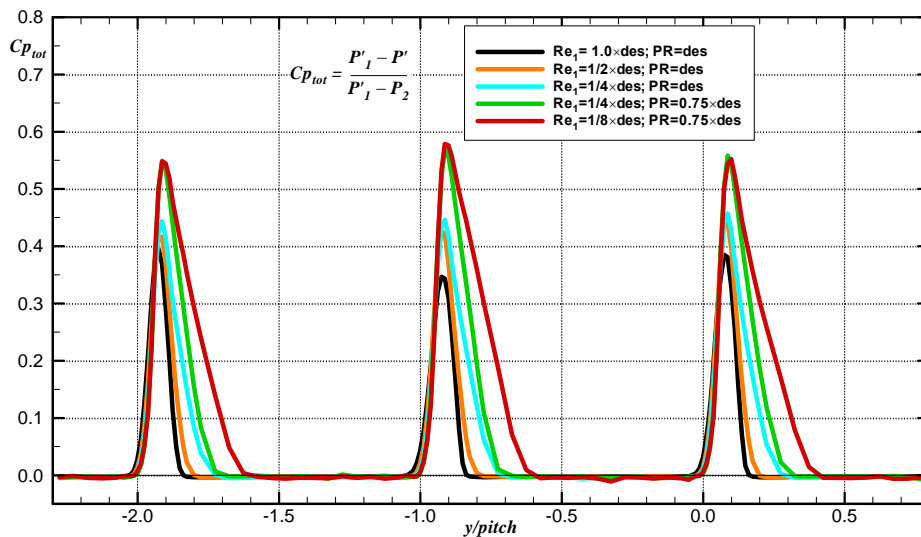
# NASA transonic linear cascade (cont.)



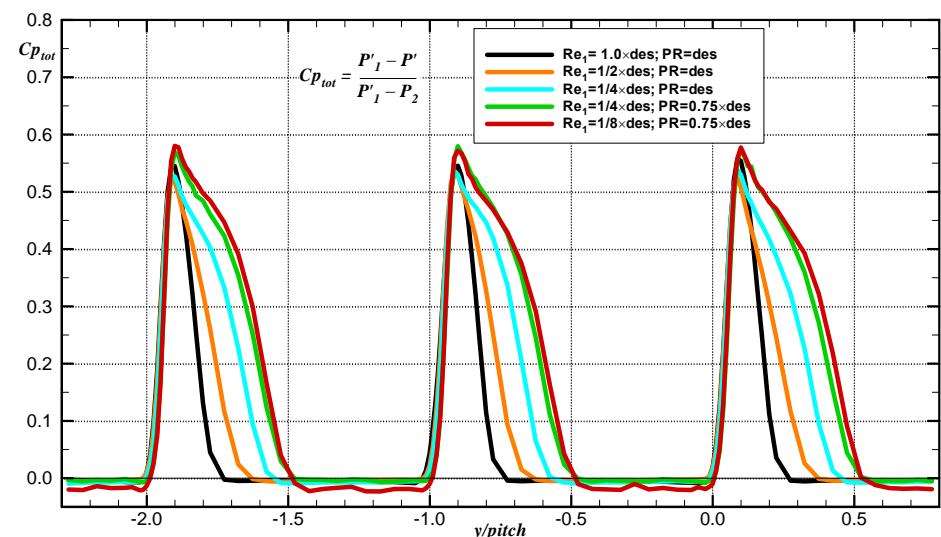
- Completed mid-span surveys of EEE tip-section
- Test cell modification for negative incidence range requirements
- First-entry VSPT blading in preparation



EEE blade pack and survey planes



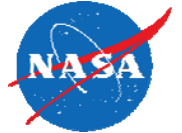
a.) -5 degrees incidence



b.) +10 degrees incidence

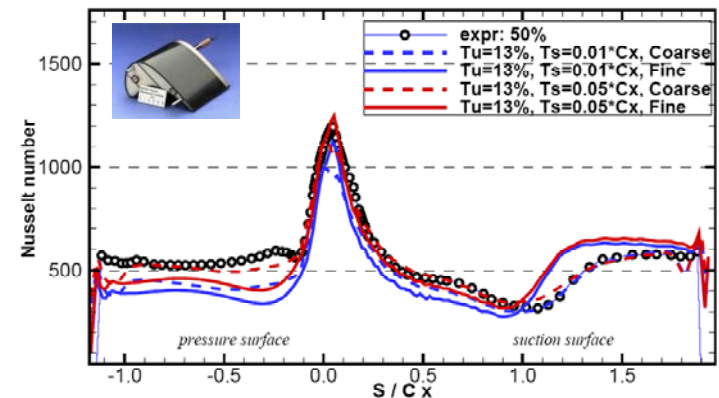
Total-pressure coefficient as a function of pitchwise position

# Computational methods for LPT/PT

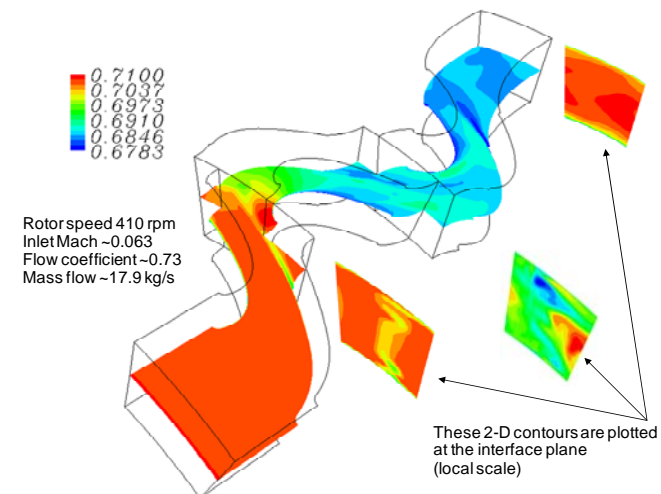


- Turbulence sub-model for transitional flow in LPTs (**A. Ameri**)
  - Evaluated turbulence models for RANS solvers
  - Selected 3-eqn model ( $\kappa_l$ ,  $\kappa$ ,  $\omega$ ) of Walters & Leylek
  - Compared to heat transfer data from GE2 LPT blade (Giel, Boyle, and Bunker)
- Multistage URANS simulation capability (**W. To**)
  - Utilize in-house code TURBO (J. P. Chen)
  - Applied to 1.5 stage LSRR turbine (Dring, UTC)
  - Openly available geometry and steady & unsteady data sets
- *AeroDynamic Solutions, Inc.* (ADS) WAND/LEO codes

*Walters-Leylek Model*

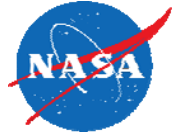


Computed Nusselt number for GE2 LPT blading  
(**CFD A. Ameri**; **Experiment P. Giel et al.**)

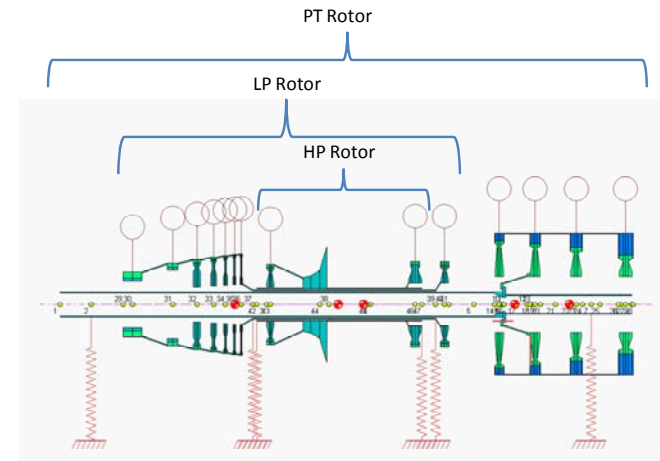


Contours of instantaneous total-pressure in LSRR multistage turbine rig computed using TURBO multiblock code (**W. To**).

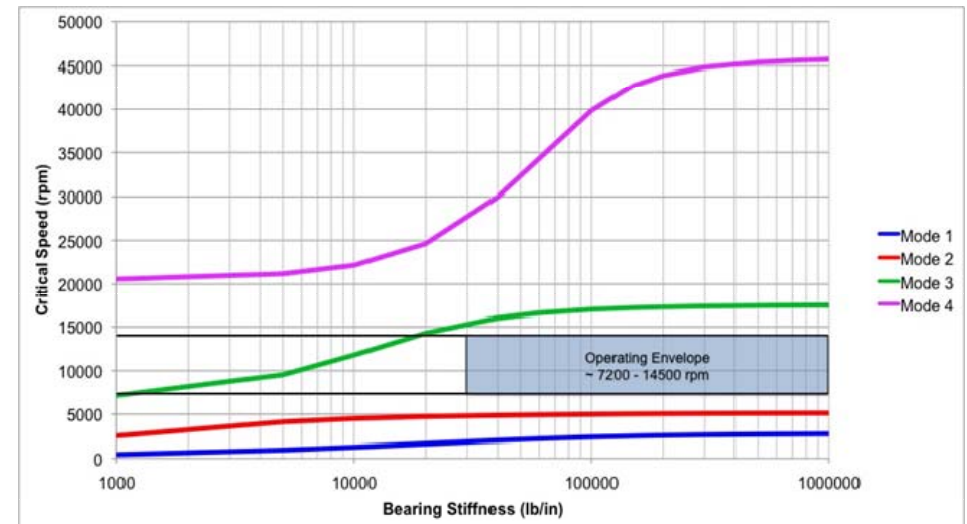
# Rotordynamics



- Rotordynamics model for LCTR w/ 50% speed range (A. Howard)
  - Model of LCTR2 HP, LP, and VSPT rotors
  - Geometry from WATE code (Doug Thurman)
  - Some assumptions on bearing location modeled after T700
- Rotordynamics model of T700-700 created
  - Supporting assessment of component test capability

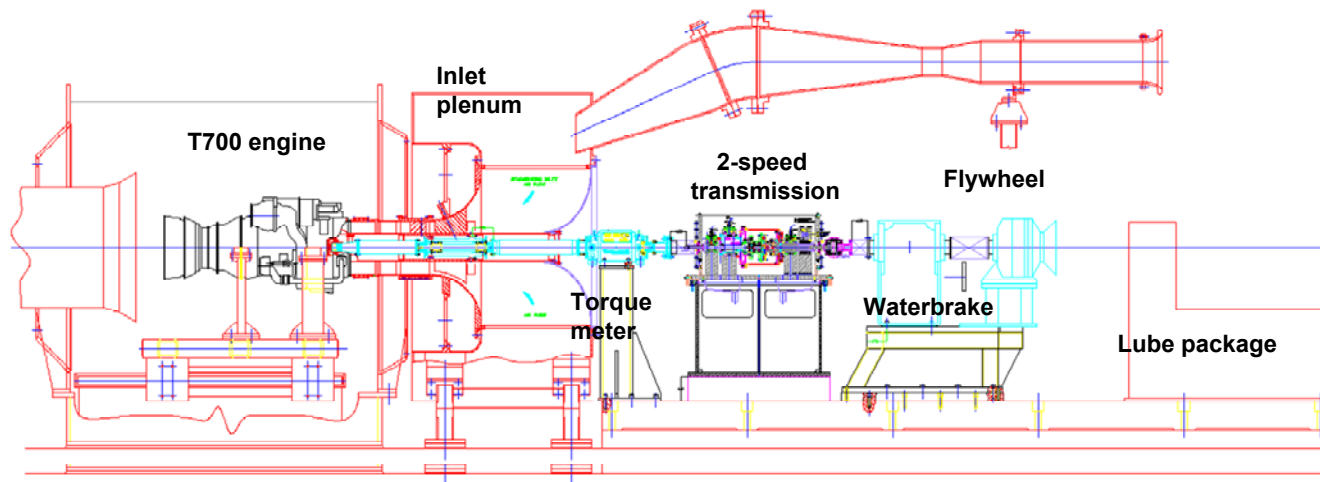
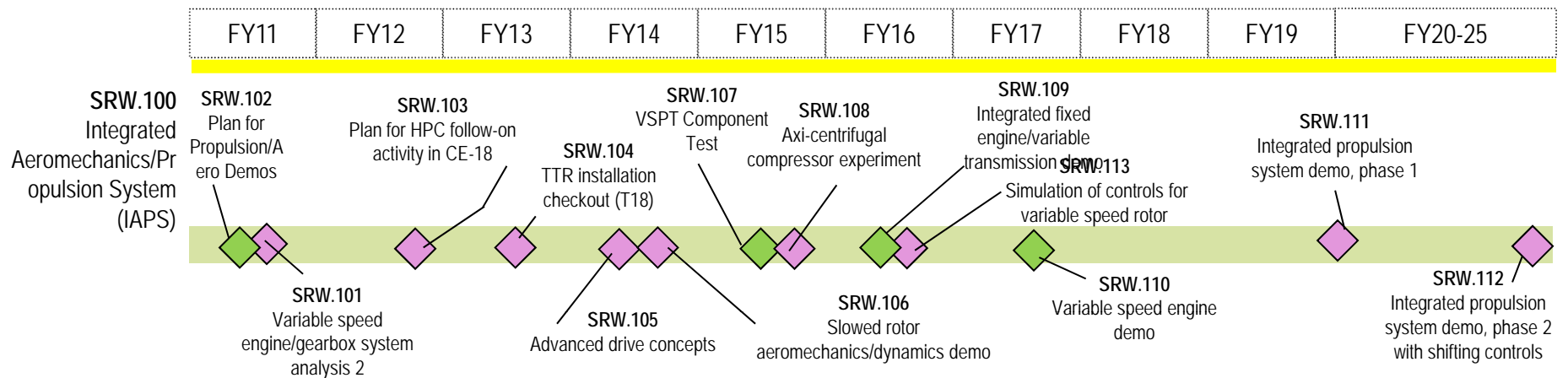


DyRoBeS model of LCTR rotors  
(A. Howard)



Critical speed map showing first four critical speeds of PT-shaft in LCTR2 operating range  
(A. Howard)

# Integrated Aero/Propulsion system (IAPS) FY25

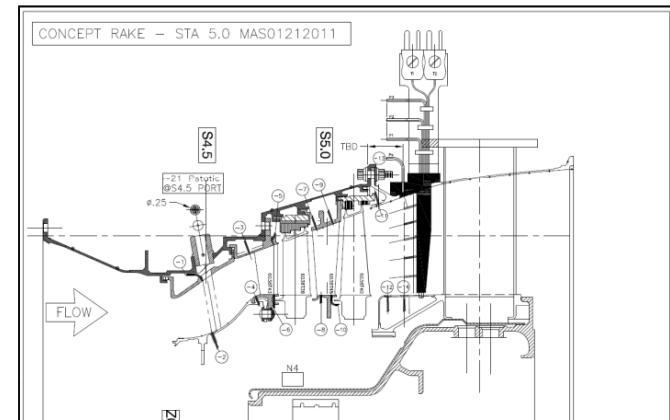


**Notional layout for integrated engine/transmission demo**  
(M. Stevens)

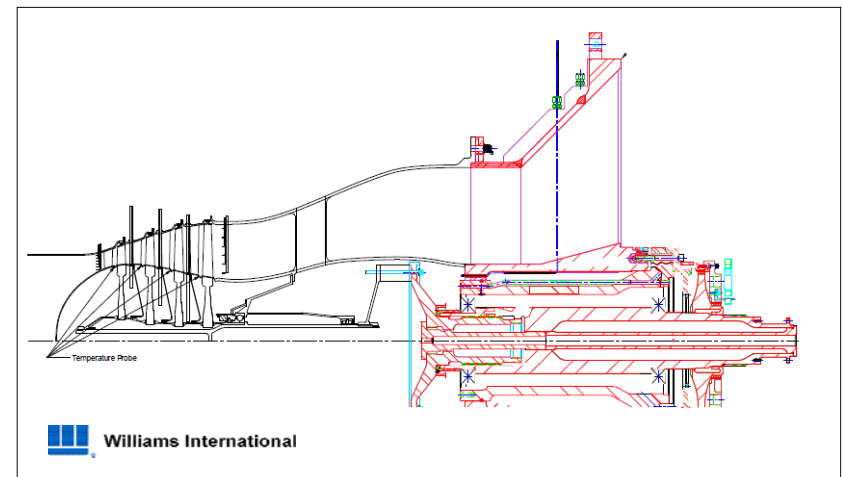
# VSPT component testing – first steps



- Assessment of in-house VSPT test capability (G. Skoch)
  - T700-700 engine in the Engine Component Research Laboratory (ECRL)
    - Engine and power absorption capability
    - Engine controls
    - Integration of rating / survey instrumentation
    - PT rotordynamics / shaft mode interactions
  - NASA GRC warm turbine test facility (W-6)
- RTAPS study contracts
  - Williams International
    - 4-stage VSPT in W-6
    - Match first and last stage Re
  - Rolls-Royce
    - Growth AE1107
    - 3.5 stage VSPT/EGV in W-6
    - Match Re at take-off & cruise
- External options being explored
  - Planned AATD 6.2 component program



**Notional instrumentation layout for VSPT component test in T700 (M. Stevens)**



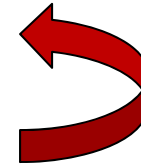
**Williams Int. VSPT for LCTR (M. Suchezky & Scott Cruzen)**

# Summary

---



- Key aerodynamic challenges of VSPT
  - Attainment of high efficiency ( $> 0.88$ ) at high work factors (2.5 to 3.5)
  - Wide incidence variation over mission - **high negative incidence**
  - Low unit Reynolds numbers ( $30 < Re/c_x < 50k /in.$ )



**Shared by variable-speed PT and fixed-speed PTs**

- Needs:
  - Low-loss, incident-tolerant vane, blade, and EGV blading
  - Ability to manage / avoid engine shaft critical speeds during VSPT speed change
- VSPT research effort at NASA GRC
  - Develop experimentally validated design methods and computational tools/modeling for design/optimization of low-loss, incidence tolerant blading
  - Continue work with industry and DoD partners to refine VSPT design / blading, and path to component and engine test

# Acknowledgements

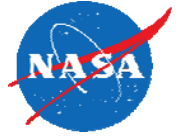
---



- Mr. Robert J. Boyle (former Distinguished Research Associate, NASA GRC) for early assistance in formulation of VSPT research effort
- Dr. Rodrick V. Chima (NASA GRC) for assistance with *rvcq3d* code
- Dr. John P. Clark (AFRL) for providing the AFRL Turbine Design and Analysis System
- Dr. Lisa W. Griffin (NASA MSFC) for permission to use the Huber meanline codes

***NASA Fundamental Aeronautics program  
Subsonic Rotary Wing project***





# BACK-UP CHARTS

# NASA GRC warm turbine test facility

